

# Integrating the Local Material of Adobe With Solar Distillation to Produce Affordable Drinking Water

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## Abstract

It is estimated that nearly three billion people are living in water scarce conditions. This research uses modeling and field studies to assess the quantity, quality, and economics of distillate produced for drinking water from a brackish water source using two single-sloped, single-basin (SSSB) distillation reactors. The reactors were constructed from adobe and concrete in San Luis Potosí, Mexico and tested from August to October of 2011. The cost of one adobe reactor with an evaporative area of 0.72 m<sup>2</sup> is 535 pesos, whereas the same size reactor made from concrete costs 770 pesos. Results show that desalination reactors made from adobe produce 848 (L m<sup>-2</sup>d<sup>-1</sup>) and reactors made from concrete produce 979 (L m<sup>-2</sup>d<sup>-1</sup>) of distillate, while similar reactors made from other materials are estimated to produce over 2100 (L m<sup>-2</sup>d<sup>-1</sup>) under similar meteorological conditions. These volumes represent approximately 10 percent of drinking water needs of a local family with typical water use habits, however, after five years of operation the unit cost of potable water would be reduced by 50%. Results also showed that the concentrations of total dissolved solids in the source water decreased from 1102 (mg L<sup>-1</sup>) to 40 (mg L<sup>-1</sup>) over the study's duration for a removal of 96% which is comparable to current desalination systems (97%). Finally, the results were modeled using a regression analysis to estimate the distillate yield based upon ambient temperature and solar radiation. The model was then applied using historical global climate data estimate the appropriateness of the adobe SSSB globally.

**Keywords:** appropriate technology, millennium development goals, sustainable development, drinking water treatment, Mexico

## 1. Introduction

Approximately 1.2 billion people live in regions with physical water scarcity while 780 million people lack access to safe drinking water (World Health Organization [WHO], 2012). By 2025 it is estimated that up to 52 countries will fall into some level of water scarcity affecting up to 3 billion people (International Water Management Institute [IWMI], 2007). As population increases and development pushes into new areas the imbalances between the supply and demand for surface water and groundwater resources will become more exacerbated. This will push users towards lower quality water sources such as brackish aquifers or more polluted surface waters and may increase the need for small scale treatment systems that can be tailored to the site specific contaminant. Furthermore, it is also estimated that 110 million people globally have been displaced due to natural disasters from 2008 through 2011 (Internal Displacement Monitoring Centre [IDMC], 2012) which highlights the need for low cost and effective point of use interventions that can be rapidly deployed in future humanitarian response efforts. There are currently several point of use or small scale treatment options on the market, like the filters made by Tulip and Water 4 Life, clay ceramic and biosand filters, chlorine addition, and various solar distillation systems, each having a unique set of advantages and disadvantages (Mihelcic, Fry, Myre, Phillips, & Barkdoll, 2009).

Solar distillation is an appropriate option for water treatment because it relies solely on the insolation energy from the sun to remove dissolved contaminants. In its simplest form, the process occurs inside the reactor where a volume of brine bearing an unwanted constituent is exposed to direct sunlight. The brine adsorbs the insolation energy throughout the day until the temperature of the brine is high enough to vaporize at the surface and produce pure water vapor that rises until it hits underside of the glass cover of the distillation reactor. At the

cover the vapor condenses and travels by gravity to a collection port and becomes part of the distillate which is free of the unwanted constituent.

The most commonly used household solar distillation technology is a single-sloped single-basin (SSSB) distillation system characterized by a relatively large thermal mass or volume of brine (Aboabboud et al., 1996). Although more effective distillation reactor designs exist, the SSSB is the only field proven solar distillation technology that provides isolated communities with an efficient way to convert brackish water into potable water (Tiwari, Singh, & Tripathi, 2003). Several studies have shown that SSSB systems are effective at removing contaminants like heavy metals, dissolved solids, and microorganisms (Fath, 1998; Hanson et al., 2004; Samee, Mirza, Majeed, & Ahmad, 2005; Kaushal, 2010; Chow, 2012). However, a concern with many of the current SSSB systems is that they do not produce potable water at a fast rate. Confronting this issue is the basis for a majority of the research in this field (Harris, Miller, & Thomas, 1985; Aboul-Enein, El-Sebaei, & El-Bialy, 1998; Mathioulakis, Voropoulos, & Belessoitis, 1999; Al-Hinai, Al-Nassri, & Jubran, 2002; Murugavel, Chockalingam, & Srithar, 2008a; Khalifa, 2011). Another issue is that the systems that are available commercially or that have been studied in detail are constructed from materials that enhance the productivity of the system while sacrificing the sustainability and feasibility of owning and operating the system. An alternative to this issue would be to construct the SSSB from a locally available material like adobe or concrete to increase the appropriateness of the small scale treatment. Appropriate technology is defined here as “the use of materials and technology that are culturally, economically, and socially suitable to the area in which they are implemented” (Mihelcic et al., 2009).

Accordingly, the purpose of this research was to design an SSSB solar distillation reactor constructed primarily from adobe, local aggregate, and cement and assess its performance for the volume and water quality of the distillate produced and the economics of the system. This topic is important for two reasons; the first is that no peer reviewed articles were identified relevant to the use of adobe or concrete in the construction of a solar still and the second is that adobe is a commonly used and readily available material in many parts of the world as one-third of the population currently lives in mud constructions (Vega, Guerra, Moran, Aguado, & Llamas, 2011). This number jumps to 50% if you consider only the developing world where the use of adobe as the primary construction material may reduce the construction costs of solar distillation reactors and possibly increase access to clean drinking water for suitable populations.

## 2. Materials and Methods

### 2.1 Site Description

This 2011 study occurred in the rural Mexican municipality of Vanegas, located approximately 240 kilometers northwest of San Luis Potosí and 70 kilometers northwest of Matehuala in the state of San Luis Potosí. The rural farming village of El Gallo is located at 24°13'12.05" N and 100°54'54.68" W, which is in Vanegas and is also an extremely arid part of Mexico that receives an average of 5.5 (kWh m<sup>-2</sup> day<sup>-1</sup>) of isolation energy (National Aeronautics and Space Administration [NASA], 2013). Access to the community was gained through a partnership between the United States Peace Corps Mexico and the Matehuala office of the Comisión Nacional de Áreas Naturales Protegidas in Mexico.

A 2011 study determined that the population of El Gallo was approximately 200 people and the average rate of water usage for drinking was 55 liters per household per week (Marlor, 2012). In the same study 55% of respondents claimed the need for more access to affordable drinking water and zero percent of the homes surveyed had reliable access to a potable water source in the opinion of the researcher. At the time of this study it was observed that many families had access to non-surface water sources that usually consisted of poorly protected wells or a filling hose attached to the irrigation water system for the croplands. In either case, the wells were drawing water from an aquifer that produced brackish groundwater. Grab samples collected on July 15th, 2011 from groundwater sources at the study location, both at the home wells and the irrigation pumps, revealed that TDS concentrations exceeded 4000 (mg L<sup>-1</sup>) in some cases, with an average concentration of 3650 (mg L<sup>-1</sup>). This exceeds the 500 (mg L<sup>-1</sup>) palatable threshold recognized by the World Health Organization (WHO, 2011).

### 2.2 Reactor Design

An SSSB distillation reactor was designed based upon considerations found elsewhere (Al-Hinai et al., 2002; Badran, 2007; Phadatar & Verma, 2007; Velmurugan & Srithar, 2010). Two prototypes were constructed, one from adobe and the other from concrete. Figures 1a-1c illustrate the basic steps involved. The adobe brick was made from a mixture of clay-rich earthen material found at the study location (about 8 cubic feet or one heaped wheel-barrel full), water (added until appropriate plasticity is achieved) and fresh or dry manure (one five-gallon bucket) from a horse, mule or cow. These ingredients were mixed by a hand-tool and foot action until a heavy

clump of material with plastic properties was produced. It was important to manage the water additions during the mixing as too much water created a non-formable paste while insufficient water was causing the brick to break apart while drying. The concrete was mixed at a ratio of 1:3:6 for the cement, sand, and gravel fractions.

The adobe or concrete was then spread into wooden forms constructed for each side of the distillation reactor and tamped hard until a tight pack was achieved; the dimensions are illustrated in Figure 2. The larger pieces were interwoven with steel-wire matting for reinforcement. Both reactors were assembled and parged with multiple applications of cement, water, and sand at a ratio of cement to water to sand of 1:2:3 to ensure water tightness.



Figure 1a

Figure 1b

Figure 1c

Figures 1a - c. The initial stage of reactor assembly involved the placement of the precast adobe or concrete blocks into the basic shape of the reactor (Figure 1a). The resulting basin was then parged with cement to ensure water tightness and erosion protection (Figure 1b). Figure 1c shows the completed field units built for this study, the adobe unit is on the right and the concrete unit is on the left

Three access ports (shown on left side of Figure 1b) were added to the basin by inserting 6 (cm) lengths of 2.5 (cm) PVC pipe into the freshly placed adobe or cement as it cured. The collection trough was made from the same cement mixture as above which is placed along the front of the basin and was tooled to include a channel for flow and occur at a slight incline towards the distillate port. The condenser cover is a piece of 3 (mm) clear glass with filed edges that is cut to fit the exact dimensions of the assembled reactor. The basin liner material is made from a cotton fabric that has been coated with black acrylic vinyl and is held in place on the bottom of the basin with general purpose silicone. The unit is finished and made ready for service by preventing vapor loss by caulking along the four edges where the basin and the glass cover meet with a general purpose silicone. One important item to consider when designing and constructing these basins is the actual evaporative area. In this case, the overall basin width and length was designed to be 100 (cm); however, if you consider the thickness of the basin wall (5 cm) and the 10 (cm) collection trough, the evaporative area would be reduced by 28% to 0.72 ( $m^2$ ). The values of water produced reported in this study have thus been adjusted to reflect one of evaporative area.

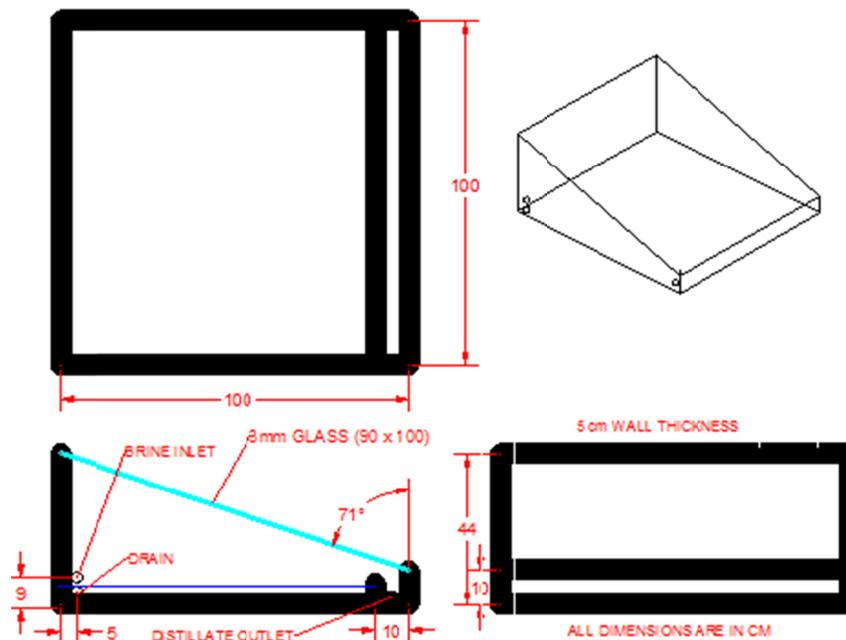


Figure 2. Detailed drawings of the single-sloped single-basin (SSSB) distillation system design used in this experiment (all units in cm)

### 2.3 Experiment Design

Thirty-three distillate samples were collected from each reactor during the time period of August 15th through October 25th, 2011. These samples were analyzed in the field for their respective volume and total dissolved solids (TDS) concentrations. Reactor distillate samples were collected in a 6000 ml plastic bottle over the course of twenty-four hours, TDS concentrations were measured with an ExStik II EC 400 Conductivity/TDS/Salinity meter (Extech, U.S.A.) and volume measurements were performed with a 1000 ml polypropylene graduated cylinder with 10-ml graduations.

On an experiment day the reactor was filled with 10 liters of brine with a measured TDS and a prepared sample bottle was placed under the distillate collection port. In this study this action typically occurred during the pre-dawn hours to ensure that the brine was exposed to the maximum amount of available sunlight that day. The reactor was then operated under ambient conditions for twenty-four hours with periodic inspections to ensure that the sample container was not open to the dusty conditions of the study location. After twenty-four hours the sample bottle was exchanged with a similar clean and empty sample container to continue the experiment for another twenty-four hour time step. Three time steps were completed before the reactor was drained and refilled with 10 liters of brine. The full sample containers were then moved inside to a clean and level workspace where TDS concentration and volume measurements were made within five minutes of sample collection.

## 3. Results and Discussion

### 3.1 SSSB Reactor Performances

A main objective of this study was to determine if solar distillation could be used to remove TDS from groundwater when earthen material is the primary construction component. Results indicate that a 96% removal of TDS was attainable in both the adobe and the concrete reactors, while the average initial TDS concentration was 1102 ( $\text{mg L}^{-1}$ ) for both (Table 1). These results compare to other analyses that looked at removal of SSSB reactors made from other materials. For example, Samee et al. (2005) utilized a reactor constructed from plywood and achieved between 85% and 98% removal when the initial TDS concentrations were 544 and 17 663 ( $\text{mg L}^{-1}$ ) respectively. Similarly, Chow (2012) observed between 95% and 98% removal with initial concentrations of 18 000 ( $\text{mg L}^{-1}$ ) for a reactor made from aluminum and steel. A 2004 publication (Hanson et al., 2004) again verifies the TDS results seen in this study with a 98% removal, but also offers some insight into the potential for removing other contaminants from the brine via solar distillation as well. The same publication also looked at the elimination of nitrate and fluoride from a brine and found a two log removal. The same study also looked at removal of fecal coliforms and concluded that a three log removal of these pathogens was possible

during the distillation process. These results suggest that the SSSB reactor designed in this study may also be capable of producing safer drinking water by removing inorganic contaminants or certain pathogens, which would be very important in many situations.

Table 1. Distillate production rate and TDS concentration in distillate: August 15, 2011 - October 15, 2011

Statistic	Adobe Unit	Concrete Unit
Mean TDS (mg L <sup>-1</sup> )	40	38
Range (mg L <sup>-1</sup> )	30 - 62	32 - 57
Sample Size	33	33
Standard Deviation	7.1	7.0
Mean Volume Produced (L m <sup>-2</sup> d <sup>-1</sup> )	0.84	0.99
Range (L m <sup>-2</sup> d <sup>-1</sup> )	0.41 - 1.2	5.8 - 1.3
Sample Size	33	33
Standard Deviation	0.15	0.26

Note: The results related to the volume of distillate produced and the TDS measurements recorded during the experiment.

In addition to the quality of the distillate produced, this study also focused on the quantity of distillate produced by the SSSB reactors remembering that a typical family in the study location requires 55 (L week<sup>-1</sup>) of potable water (Marlor, 2012). Figure 3 illustrates these results obtained during the study period for both the adobe and concrete SSSB units. The highest values of distillate observed in this experiment occurred during August which is the fifth sunniest month at the study location and the sunniest month of the three in this study. Table 1 summarizes the results shown in Figure 3 and show that the average production rate of the adobe reactor was 0.84 (L m<sup>-2</sup>d<sup>-1</sup>) compared to 0.99 (L m<sup>-2</sup>d<sup>-1</sup>) for the concrete unit. A 17% larger yield was thus observed in the concrete unit than in the adobe unit over the same time period.

This study was concerned with how an appropriate earthen material SSSB distillation system would perform compared to similar SSSB reactors made from other materials, and the results do not favorably compare to observations of other SSSB systems. For example Nafey, Abdelkader, Abdelmotalip and Mabrouk (2002), operated an SSSB in Egypt that was made from black and white painted metallic (unspecified) material and collected between 4.3 and 5.9 (L m<sup>-2</sup>d<sup>-1</sup>) of distillate. In Pakistan, Chow (2012) found that his aluminum SSSB unit produced between 0.8 and 3.8 depending on the season. Other research has shown that an SSSB made from black Plexiglas produced between 1.5 and 2.5 on the campus of the University of Bahrain and that 3.1 was produced also in Pakistan (33°N) by a SSSB made from plywood and improved with hard-foam insulation (Al-Karaghoulis & Alnaser, 2004; Samee et al., 2005). Aside from the materials used in these studies, the color of the material also plays an important role in the amount of distillate produced. For example, a basin that is darker in color will be more effective at absorbing the incoming solar radiation and therefore have greater distillation potential than a similar basin made from a lighter colored material. This observation suggests that the adobe SSSB system could be painted black to increase its productivity.

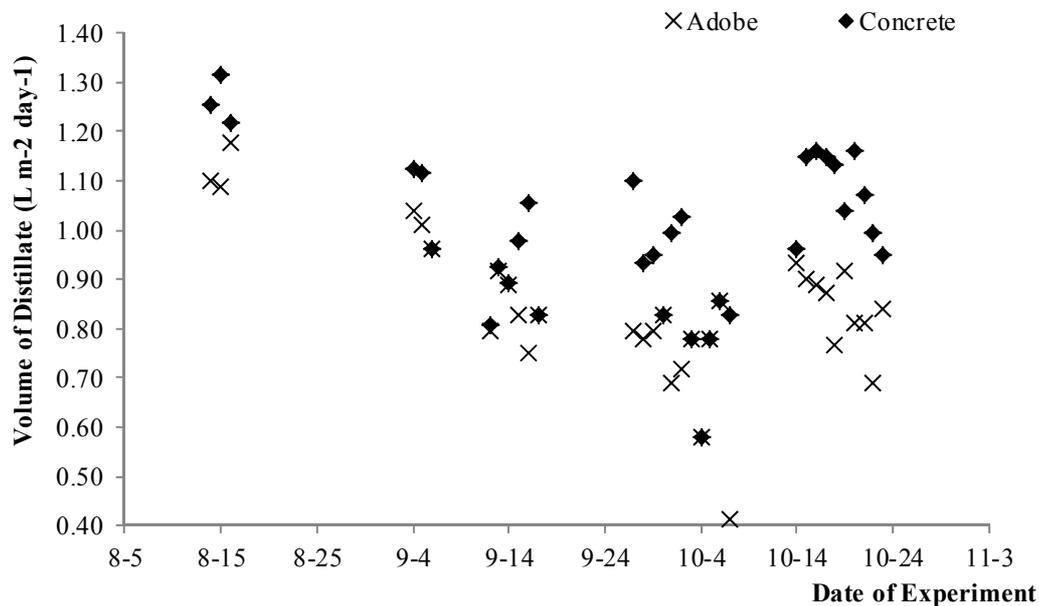


Figure 3. The amount of distillate produced ( $L m^{-2} day^{-1}$ ) during each experiment day from the adobe and concrete field units. Reactor area was  $0.72 (m^2)$

The differences in distillate production rates between this study and others might also be attributed to the variances in the study location that the unit was operated at. Because insolation and ambient temperature are the primary meteorological parameters that influence how much distillate is produced by an SSSB (Khalifa, Hamood & Ahmad, 2009; Nafey et al., 2001; Mathioulakis et al., 1999) the insolation rates and temperatures for each location should be compared to consider the impact that the study location may have on the production rate. Consulting the surface meteorology and solar energy database maintained by NASA (2011) the following annual average insolation values were obtained: Egypt  $5.3 (kWh m^{-2} day^{-1})$  (maximum 7.7), Pakistan 5.1 (maximum 7.5), Bahrain 5.6 (maximum 7.7), and San Luis Potosi (Mexico) 5.5 (maximum 6.6). In addition, the average ambient temperatures were found to be 21.0, 18.0, 27.4 and 16.7 ( $^{\circ}C$ ) respectively at the four sites. Upon comparison of these data points it is not clear that the study locations vary much in the average amount of insolation energy they receive. However based on further comparison of the maximum amount of insolation received paired with the average ambient temperature at each location provides a significant contrast in the meteorology of the study locations. For example, the comparison sites receive approximately 15% more maximum insolation energy and they also are approximately 8% to 60% warmer than the study location. This favorable combination of more heat and available solar energy could be used to explain some of the lower distillate production rate observed for the earthen SSSB reactors.

The differences in production rates might also be attributed to the variances in the construction materials. Relative to other materials, earthen materials like adobe have higher thermal capacities (Revuelta-Acosta, Garcia-Diaz, Soto-Zarazua, & Rico-Garcia, 2010). Thermal capacity characterizes the amount of heat required to change a substance's temperature by a given amount. In other words, a higher heat capacity indicates that more energy (heat) can be stored inside the mass. This affects the distillation process in a negative way because more energy can be transferred and stored into the basin material, essentially making the heat temporarily unavailable to induce evaporation. An advantage to this property relates to the nocturnal distillate production rate. This occurs when there is no more solar insolation available to drive the evaporation process and the stored energy inside the adobe basin will provide heat for a period of time, which should effectively increase the volume of distillate produce over a twenty-four hour period.

The thermal conductivity of the adobe, or earthen materials is also important. It is the quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area, due to a unit temperature gradient under steady state conditions. For example, a distillation reactor made from plywood will have a thermal conductivity of  $0.14 (W m^{-1} K^{-1})$  while a reactor basin made from adobe or concrete will have a thermal conductivity of  $1.5 (W m^{-1} K^{-1})$  (Incropera & De Witt, 1990). This indicates that the basin constructed from

adobe would be more likely to lose heat through its walls than the wooden reactor and may explain the difference in distillate production rate between the systems compared above.

An interesting application of the volumetric results in this study was the ability to predict how the SSSB reactor might operate throughout the remainder of the year or at other geographical locations. Recalling that the quantity of distillate produced is heavily influenced by the insolation energy and the ambient temperature of the location, Excel was used to develop a model to estimate the distillate production of the adobe unit based upon the measured values of insolation energy ( $H$ , kWh m<sup>-2</sup> day<sup>-1</sup>) and temperature ( $T$ , °C). These two parameters were measured by instrument at a government run weather station approximately 75 kilometers from the study location in Matehuala, SLP.

$$\text{Volume Distillate (L m}^{-2}\text{ day}^{-1}) = 0.15H + 0.003T \quad (R^2=.988) \quad (1)$$

Applying Equation (1) to the local maximums identified in the NASA database (maximum solar insolation = 6.5 kWh m<sup>-2</sup> day<sup>-1</sup>, ambient temperature = 20 °C) the highest amount of distillate produced at the study location is projected to be 1 (L m<sup>-2</sup> day<sup>-1</sup>). If the same calculation process was used to obtain the maximum expected yield for the comparative locations examined earlier, the adobe reactor examined in this study would be expected to produce up to 1.23 (L m<sup>-2</sup> day<sup>-1</sup>). Figure 4 summarizes the estimated annual production potential of the adobe SSSB unit from this study using Equation (1) and the specific solar and surface weather data obtained from NASA for the study location. The average daily production rate over the course of the year was determined to be 0.89 (L m<sup>-2</sup> day<sup>-1</sup>) (compared to a value of 0.84 reported in Table 1). Calculating the area under the curve in Figure 4 reveals the total amount of distillate that could be expected at the study location, which in this case is 325 liters of water annually for every square meter of evaporative area utilized.

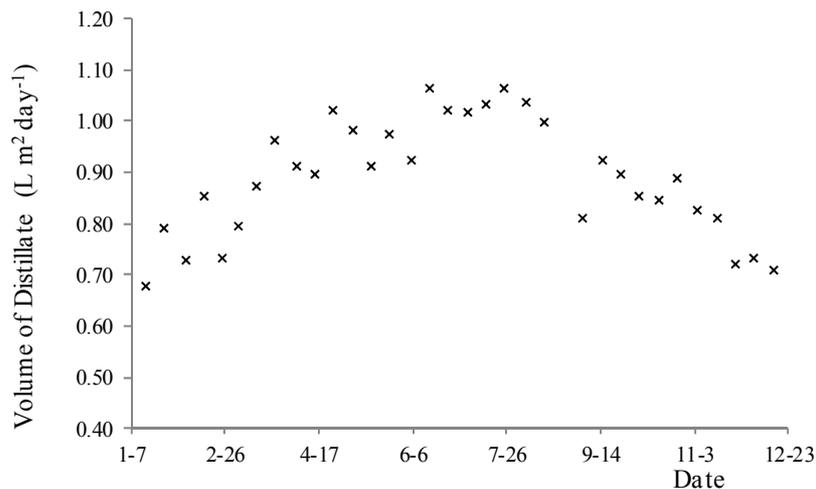


Figure 4. Estimated amount of distillate produced (L m<sup>-2</sup> day<sup>-1</sup>) throughout the year at the study location in the adobe single-sloped single-basin (SSSB) distillation reactor using Equation (1) and historical climate data

The 325 liter volume (assuming 1 m<sup>2</sup> of evaporative area) represents 11% of the 2860 liters required annually by a typical household in the study location. Therefore, it can be concluded that the adobe SSSB reactor in this study does not meet the demand for potable water in the location. However there are several options available to increase productivity of the SSSB unit. The first few would be to incorporate design changes to the system, namely: increasing the reflectivity of the inside of the basin, painting the entire basin a darker color, adding black dye to the brine to increase the absorption rate of insolation energy, and using less brine volume overall to decrease the time required reach an evaporative temperature. Another solution to increase the total volume of potable distillate would be to dilute it with untreated brackish water until the TDS is at a level close to the 500 (mg L<sup>-1</sup>) WHO threshold. In this case, assuming a local average brine TDS of 1102 (mg L<sup>-1</sup>) and a TDS target of 450 (mg L<sup>-1</sup>), the annual volume of 325 liters of distillate produced could be diluted with 205 liters of brackish water to obtain 530 liters of potable water that would thus satisfy almost 19% of the typical demand. This method is not recommended for use with all waters if pathogens are suspected to be present in the blending water.

We also considered the global reach of the adobe SSSB unit by performing suitability mapping using ArcMap10.1 by ESRI (Redlands, CA). The map consisted of two raster layers disseminated into one kilometer grids, one representing the maximum temperature and the other representing the maximum direct normal radiation observed for each grid cell. These climate variables characterize the past 22 years of meteorological data collection by NASA. Equation (1) was then applied to the layers to determine the maximum quantity of distillate that could be expected from a similarly constructed adobe SSSB operating at various locations. Figure 5 represents the ArcMap output which is the amount of distillate expected to be collected if the local maximum insolation energy and maximum temperature occurred simultaneously on a given day. The actual values will vary depending on the local conditions each day. As expected, the arid regions of the planet like sub-Saharan Africa and most of the Middle East are the dominant producers in this scenario because of their high ambient temperature and intense solar radiation levels.

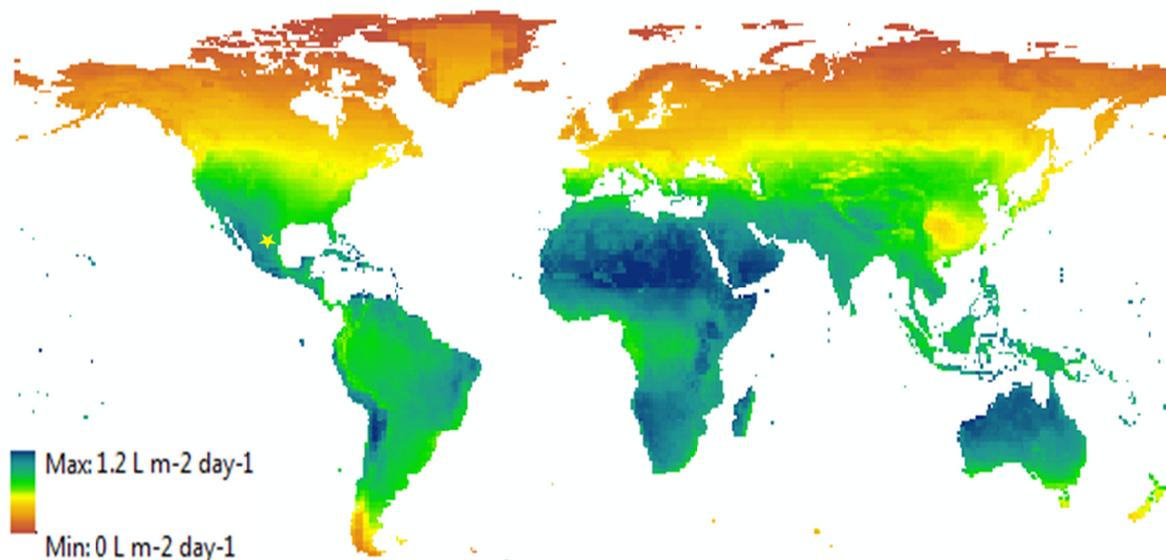


Figure 5. A composite map of the estimated maximum amount of distillate produced ( $L m^{-2} day^{-1}$ ) at any location on the globe for a single-sloped single-basin (SSSB) distillation system constructed from adobe using Equation (1), with inputs of observed local maximum temperature and direct normal radiation (NASA, 2013). The yellow star indicates the study location of this research

### 3.2 Engineering Economics

The final component of this study was to evaluate the economic feasibility and benefit of the adobe SSSB distillation reactor. A 2011 study of the income levels of the families found that the average monthly income in the area is \$3850 pesos while the maximum monthly income is approximately \$10 300 pesos (Marlor, 2012). The costs associated with building and maintaining the SSSB reactors are listed in Table 2, at the time of this experiment the conversion from USD to pesos was 1 to 12.3. All of the materials utilized in the design of the reactor were available within the typical traveling range of the community member. For this project the total cost to construct the adobe unit was \$535 pesos, or \$44 USD, while the concrete unit was 40% higher due to larger concrete and aggregate requirements. In many cases there will be local supplies of sand and gravel that can be exploited to reduce the costs of the units. In comparison, the system used in Pakistan by Samee et al. (2007) cost \$5040 PKR or about \$90 USD, and the cost of similar commercial SSSB units can be \$250 and as high as \$1000 USD. Overall, for the average family in the study location it would cost about 1% of their annual income to own and operate one adobe SSSB unit.

Table 2 also provides the estimated unit economic value of the distillate produced by the reactors. This information is based upon the predicted annual average derived from Figure 4 ( $325 L yr^{-1}$ ) of the adobe test unit and the costs to own and operate the system. It is assumed that \$40 pesos will be required on an annual basis to purchase silicone to reseal the system and that the lifespan of the glass condenser is at least five years. Based upon these parameters the economic analysis shows that the cost to the end user of distillate from the adobe SSSB will decrease overtime from \$1.78 (pesos  $L^{-1}$ ) in year one to \$0.45 in year five. Comparing this to the

current unit cost of potable water to the community of 0.875 (pesos L<sup>-1</sup>) it can be concluded that the SSSB unit in this study would be more affordable over time.

Table 2. Costs associated with owning and operating the SSSB examined in this study

Material	Adobe Unit (pesos)	Concrete Unit (pesos)
Cement	15	150
Sand/Gravel	50	150
Glass Cover	200	200
Plumbing Connections	50	50
Wood Base	100	100
Black Acrylic Fabric – Basin Liner	80	80
General Use Silicone	40	40
<b>Total Construction Cost</b>	<b>535</b>	<b>770</b>
Estimated 2-Year Volume Produced (Lm <sup>-2</sup> )	646	758
Unit Cost (pesos L <sup>-1</sup> )	0.95	1.07
Estimated 5-Year Volume Produced (Lm <sup>-2</sup> )	1616	1895
Unit Cost (pesos L <sup>-1</sup> )	0.45	0.51

Note: The total cost of materials for the earthen material SSSB distillation reactors used in this study, as well as, estimates of the unit cost (pesos L<sup>-1</sup>) of the distillate produced after two and four years.

Let us consider the distillate produced in terms of a revenue source, or that the value of the 325 liters of potable water produced (Figure 4) by one distillation unit at a price of \$0.875 pesos would be worth \$246 pesos annually. If we apply this revenue to the initial construction cost of \$535 pesos (Table 2) at a conservative interest rate of 4% over four years using a net present value function, it can be determined that the net present benefit of constructing one adobe SSSB reactor is \$342 pesos to the user over four years and the breakeven point would occur between years two and three. The net present value calculation assumed that the glass condenser would be replaced every two years and that \$80 pesos of silicone would be needed each year for maintenance purposes. This result illustrates the affordability of the adobe system and the potential for the user to actually recover their initial investment.

This analysis also points to the long-term commitment this technology requires to become effective because multiple years of operation are required to realize a return on the initial investment to construct the system. Given this situation it is important to also consider the maintenance requirements of the adobe SSSB unit and if the user is capable of performing the task themselves because limitations here will result in non-use of the system once it becomes worn. In this case, the major maintenance component involves weekly monitoring of the silicone seal between the basin and the condenser cover. This can be performed by visual inspection by the user and the silicone can be obtained locally. The other major item that will require maintenance is the condenser cover itself because it is made from glass and has a potential to break during operation and maintenance activities. In this case the replacement of the glass would require a significant investment from the user which may reduce the ability to perform this task. It may be possible to use plastic instead of glass for the condenser to reduce this risk but materials like that tend to lose their transparency quickly when exposed to direct sunlight which would reduce the effectiveness of the system.

#### 4. Conclusions

Overall the SSSB reactors made from adobe and concrete have successfully removed a significant portion (96%) of TDS from a brackish groundwater source while reducing the cost of potable water by 50% after five years of use. However, despite the economic feasibility of the system an improved distillate production rate is desired for the system to be more effective at improving access to potable water. There is a substantial amount of research that has been published regarding the optimization of solar distillation systems, however, many of these modifications are difficult to achieve in settings similar to this study location due to cost or availability. The next step in this research is to determine the improvements that add volume production without taking away from the affordability and sustainability of the earthen material SSSB distillation unit.

Furthermore, it is important to recognize that the total benefit of the SSSB reactor examined in this study depends upon more than just the value of the water produced. It is also related to the favorable impacts that this particular point of use treatment could have on the health and time constraints of the family. For example, in

Africa, a proposed rain water harvesting system implemented in urban slums to improve access to water was estimated to nearly double the reduction in disability-adjusted life years of the end users (Fry, Cowden, Watkins, Clasen, & Mihelcic, 2010) which often translates to more time to generate income so the income potential for the family increases.

Another important point to consider is how much human energy is required to collect drinking water via different methods and how that relates to the amount of embodied material energy in each. Held, Zhang and Mihelcic (2012) has quantified and compared these two types of energies and found that when more material and service inputs are required early in the life cycle then less direct human energy will be spent on collecting water overall. The conclusion of that study highlights the need for implanting lower embodied-energy technologies that reduce direct human energy during use. The application of this information to the adobe SSSB unit is interesting because one would expect there to be less embodied energy in the material and service component when compared to the concrete unit or SSSB units made from other industrial materials and therefore the user would expend less energy overall to obtain potable water. However, because the briny groundwater still needs to be collected and transported to the home for treatment it appears that the SSSB follows the patterns identified by Held et al. (2012) that more sustainable technologies may not reduce the direct human energy burden.

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